PHOTOMASK

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# Mask patterning for the 22nm node using a proton multi-beam projection pattern generator

**Joerg Butschke, Mathias Irmscher, Holger Sailer, Lorenz Nedelmann, and Marcus Pritschow,** IMS Chips, Allmandring 30a, D-70569 Stuttgart, Germany

**Hans Loeschner and Elmar Platzgummer,** IMS Nanofabrication AG, Schreygasse 3, A-1020 Vienna, Austria

## ABSTRACT

Decreasing throughput of high-end pattern generators and insufficient line edge roughness (LER) of chemically amplified resists (CAR) might become limitations for future mask making. An alternative could be the introduction of less sensitive resists, linked to a turning away from today's electron beam pattern generators. Moderate exposure doses of around 25µC/cm$^2$ could be achieved for non-CAR materials like HSQ by the use of 10keV protons. Targeting optimized absorber performance, Shin-Etsu has developed an Opaque-molybdenum-over-glass (OMOG) material, designed for 32nm mask technology and beyond. This hard mask concept allows using thin resist layers, as required by an ion beam exposure. Goal of this work was to assess a HSQ based non-CAR process using a multiple ion beam pattern generator including subsequent transfer into the absorber by dry etch processes. Proton exposures have been done on the IMS Nanofabrication proof of concept tool which is designed for 40,000 programmable ion beams. For comparison, an electron based reference process has been set up in parallel to the proton multi-beam approach. Hard mask opening and subsequent absorber etching have been accomplished in a state of the art mask etcher. Assessment of the process flow has been done in terms of feature profile, LER and resolution capability.

## 1. Introduction

Two main challenges of future mask making are the decreasing throughput of the pattern generators and the insufficient line edge roughness of the resist structures. The increasing design complexity with smaller feature sizes combined with additional pattern elements of Optical Proximity Correction (OPC) generates huge data volumes which reduce correspondingly the throughput of conventional single e-beam pattern generators. On the other hand the achievable line edge roughness when using sensitive chemically amplified resists does not fulfill the future requirements. The application of less

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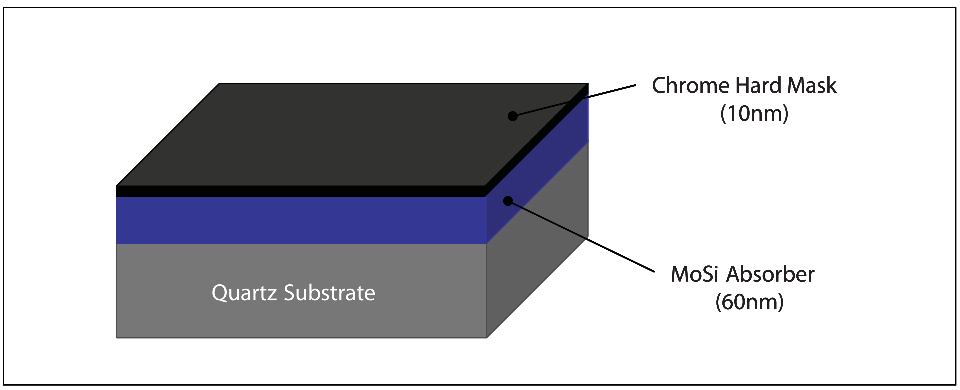


*Figure 1. Opaque-Molybdenum-Over-Glass (OMOG) material.*

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SPIE

# Editorial

## Best Wishes for the New Year

**Brian J. Grenon,** BACUS President

I'd like to take his opportunity to wish everyone the best for the New Year. In spite of the lagging economy in 2008 we as an organization have had our successes. The 2008 Photomask Symposium was a success, however the submissions and attendance was down, consistent with the current economic environment. We look forward to seeing you at the SPIE Advanced Lithography Symposium from February 22 through 27 in San Jose. During that time we will have our annual panel discussion that will be moderated by Paul Luehrmann of ASML and Larry Zurbrick of Agilent. The topic will be: **"The Future": Where will Reticles be by the end of 2013? Five years from now: Dateline - Friday the 13th, December 2013 ... Where will the reticle industry be? Will we continue to use our current glass plates? How will EUV and it's reflective masks have changed things? Maybe 1x Imprint Masks will be in vogue? Maybe none at all (Maskless)...!?** Our panel of master prognosticators will set to creatively solve the problems of the Universe and determine the answers to these questions. Schedule panelists are: Customer view: Paul Ackmann (AMD), EDA view: Tracy Weed (Synopsys), Maskmaker view: Chris Progler (Photronics), Maskmaker view: Franklin Kalk (Toppan Photomasks). I'm sure we all have opinions as to what the future holds for the industry. We invite you to attend and share your views or debunk the views of the panelists. This event is meant to be entertaining and informative.

Also, please note that this year's Photomask Symposium will be held earlier this year in Monterey from September 14 through 18, the Co-chairs for the Symposium are Larry Zurbrick of Aligent Technologies, Inc. and Warren Montgomery of CNSE/SEMATECH. We encourage you to participate in the 2009 Photomask Symposium and look forward to seeing you in the coming year.

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**Managing Editor/Graphics** Linda DeLano
**Advertising** Teresa Roles-Meier
**BACUS Technical Group Manager** Pat Wight



SPIE

P.O. Box 10, Bellingham, WA 98227-0010 USA
Tel: +1 360 676 3290 or +1 888 504 8171
Fax: +1 360 647 1445
SPIE.org
customerservice@spie.org

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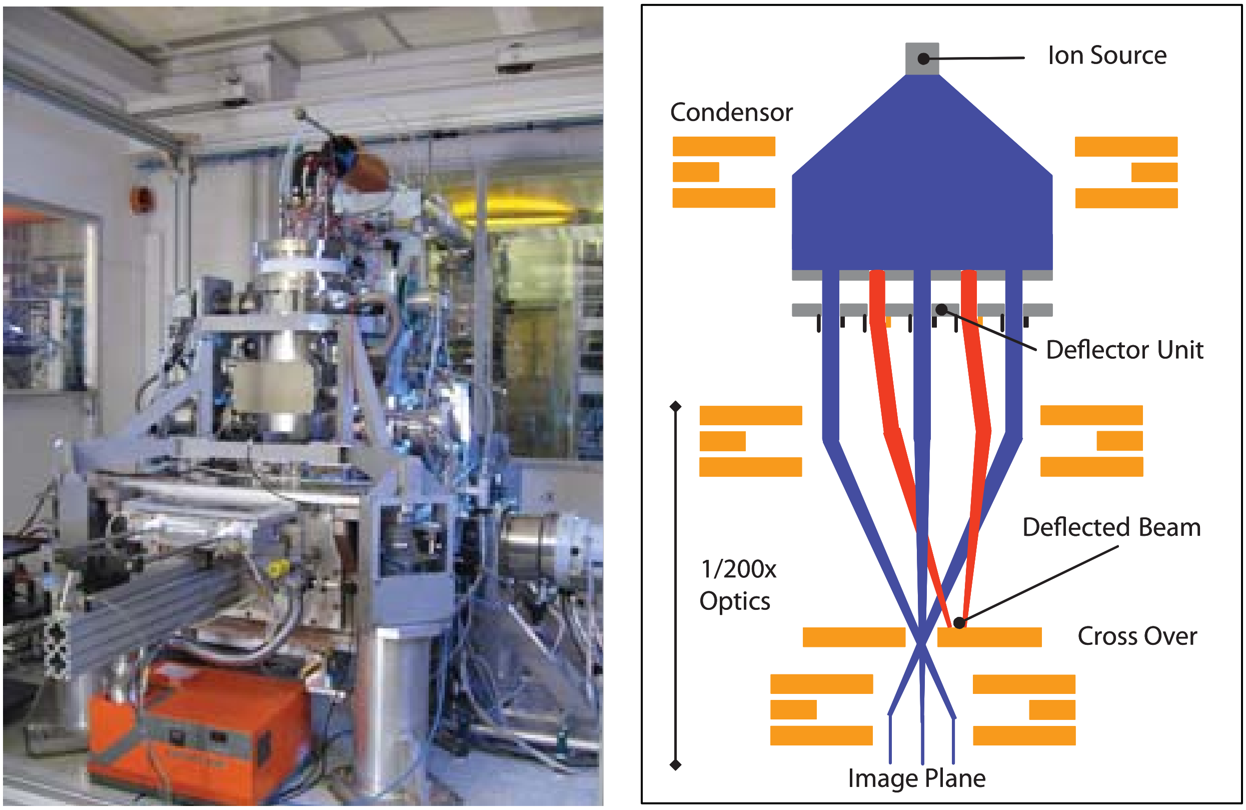


*Figure 2. CHARPAN Prototype Tool: Setup (left) and schematic diagram (right).*

sensitive resists may provide an improved roughness, however on account of throughput.

The multi-beam approach[1] is considered to cope with the throughput problem. Turning away from the electrons and turn to protons instead, a second limiting factor may be overcome: Due to forward scattering in resist, resolution enhancement for electron beam exposure systems can mainly be achieved by increasing the acceleration voltage. That means the already weak interaction in between electron and resist molecule is further reduced. As a consequence, the exposure dose and therefore the exposure time per mask increases again. Due to the higher mass, protons show much stronger interaction with resist emitting a high number of low energy (~eV) electrons along their path. Therefore, the dose to clear is much lower compared to electrons. On the other hand, the strong interaction narrows the penetration depth in the resist. Using 10keV protons, maximum thickness of the resist is in the range of 50nm while 50keV protons allow the patterning of a 100nm thick resist film.[2]

Independent of such minds, development of special stacks of hard mask coated binary blanks has started and some of them are already available provided by commercial suppliers. The driving force of this development is the improvement of the absorber performance suitable for 193nm lithography at the 32nm node and below. A promising approach is e.g. the Opaque-molybdenum-over-glass (OMOG) approach (Fig. 1) as recently presented by Shin-Etsu.[3,4] The chrome hard mask on top of the material can be easily structured even when a very thin resist layer is used. Using a different stack provided by Hoya,[5] also a resistless patterning approach has been studied.[6] Summing up, the development of these kinds of materials offers a new opportunity using proton multi-beam pattern generators.

## 2. Process flow and experimental

### 2.1 Blank Material

Special stacks of hard mask coated binary blanks were already available. They were dedicated for resolution improvement using at first a thin resist for the structuring of the hard mask. Shin-Etsu OMOG blanks, consisting of the quartz substrate, a MoSi absorber and a thin chrome hard mask layer on top have been used for all experiments.

### 2.2 Resist

Blanks were coated with Hydrogen Silsesquioxane (HSQ) which is cross linked during electron or ion exposure by the reaction with water molecules [7]:

$$2H_xSiO_{(4-x)/2} + H_2O \rightarrow 2SiO_{(5-x)/2} + (1+x)H_2$$

Using a suitable alkali developer, exposed pattern remain as SiO2-like features on the mask. To obtain the desired resist thickness, HSQ FOX-12 was diluted with MIBK in a ratio of 1:3.

### 2.3 Tool Set

HSQ coating was done on our experimental setup based on the developer tool Hamatech ASP5000 and a one-way dispense system. The subsequent soft baking was performed on the Hamatech zone-controlled hotplate APB5500.

Electron exposure was done with a variable shaped electron beam writer Vistec SB352HR, operating at 50kV with a beam current of 20A/cm$^2$. This pattern generator offers an address grid of 1nm which is beneficial for the tuning of sub 100nm patterning. Based on the proven SB35x platform, the tool is specified for 45nm extended dense

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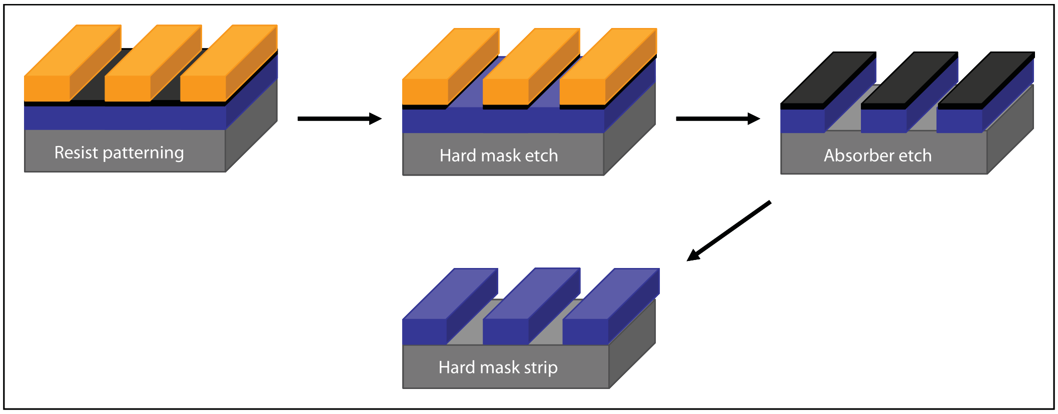


*Figure 3. Schematic OMOG process flow.*

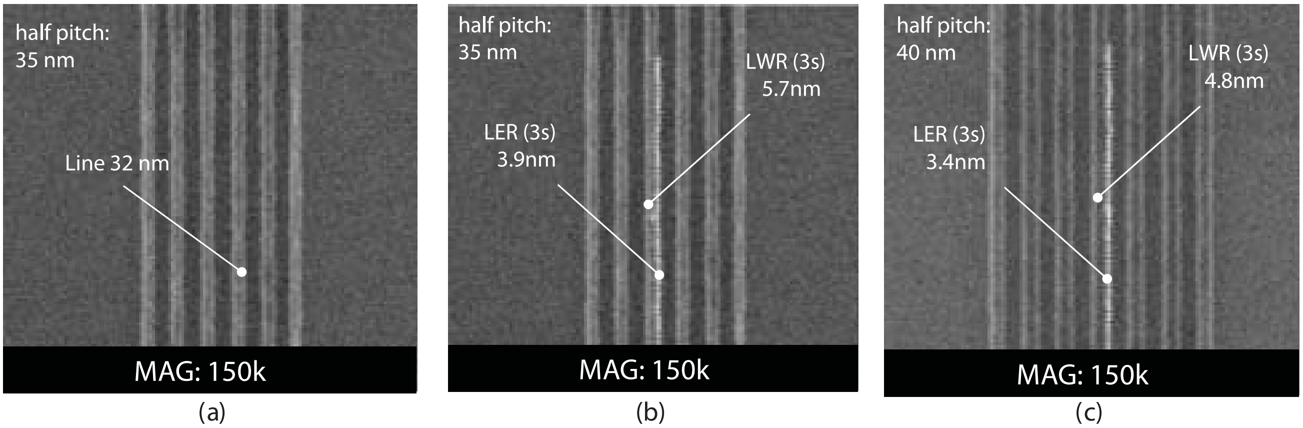


*Figure 4. HSQ patterning process using 50keV electrons: CD (a), LER/LWR for 35nm HP (b) and 40nm HP (c).*

lines and 35nm iso lines as well. The pattern generator and all resist processing tools are equipped with SMIF handling.

As HSQ is no standard resist at our site, development was accomplished in a bowl using 25% Tetramethylammonium Hydroxide (TMAH) and a rinse process afterwards. Fortunately HSQ is much more robust against environmental effects and airborne contaminations than today's CARs.

For chrome hard mask etching a GEN IV process module of an Oerlikon mask etch cluster and chlorine-oxygen chemistry was used. The subsequent hard mask-to-MoSi transfer etching process was done at the same tool on a GEN III process module using fluorine chemistry.

CD measurements were done on a state-of-the-art mask metrology system Vistec LWM9000. For all x-section SEM pictures, a LEO 1560 SEM has been used.

### 2.4 Proton Multi-Beam Exposure Tool

All proton multi-beam exposures were done on the PMLP (Projection Mask-Less Patterning) multi-beam tool (Fig. 2) located at IMS Nanofabrication AG in Vienna. This tool, developed as part of the European project CHARPAN (Charged Particle Nanotech) [8], is a proof of concept tool of an ion multi-beam projection pattern generator, designed for 40,000 programmable ion beams. For this work, the tool was operated with protons at 10keV. Currently it provides an exposure field of 25µm x 25µm. For larger fields, the exposure has to be stitched. While the automatic stage is not completed, this can be done by a manual movement of the mask substrate relative to the beam. In addition to the programmable multi-beam mode, the tool is also capable of using special silicon stencil masks for patterning in a static mode. The beam array generated by this technique can also be shifted inside the exposure field using a multi pole. The large ion optics demagnification of 1:200 easily allows the realization of small patterns. Due to the missing tool automation and the high number of exposures especially needed for x-sections, a decision was made for the second (static) mode.

### 2.5 Layout

For the electron beam based reference process, several features of different sizes have been arranged in a dose row. The layout consist of groups of seven lines in a 1:1 pitch of different widths (35nm, 40nm, 45nm, 50nm, 60nm, 65nm, 70nm, and 100nm) as well as fields of extended dense lines. In addition, a shrunk metal layer has been added to demonstrate the real device case. Data preparation was done with MGS 7.39 correction program. The total exposure time of a 2x2 array of the entire pattern was calculated to be around 6 hours.

For the proton beam based process, three different patterns have been printed: 40nm L/S in a 1:1 pitch, 80nm L/S in a 1:1 pitch, and a sequence of 60nm and 40nm L/S. In addition, a cleavable array

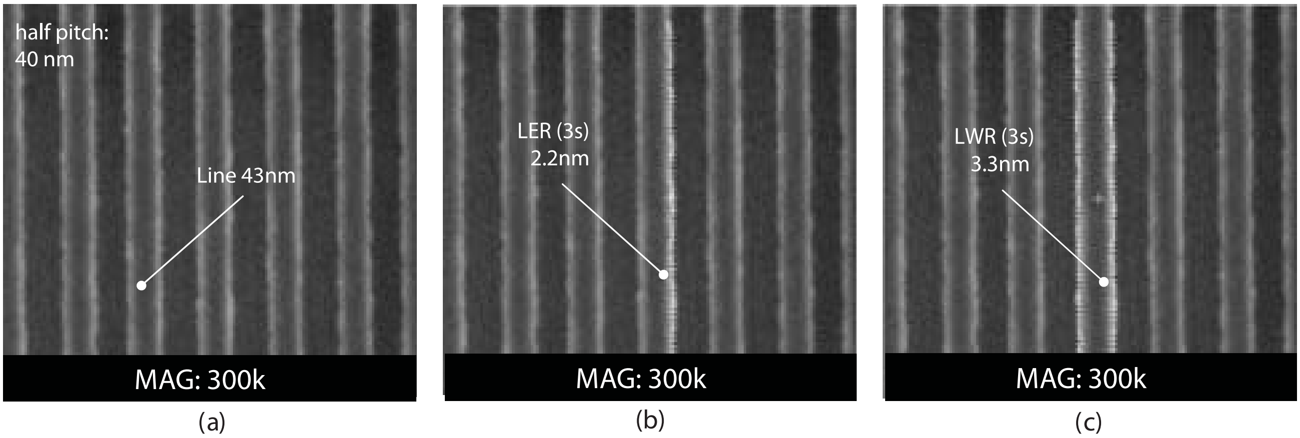


*Figure 5. HSQ patterning process using 10keV protons: CD (a), LER (b) and LWR (c).*

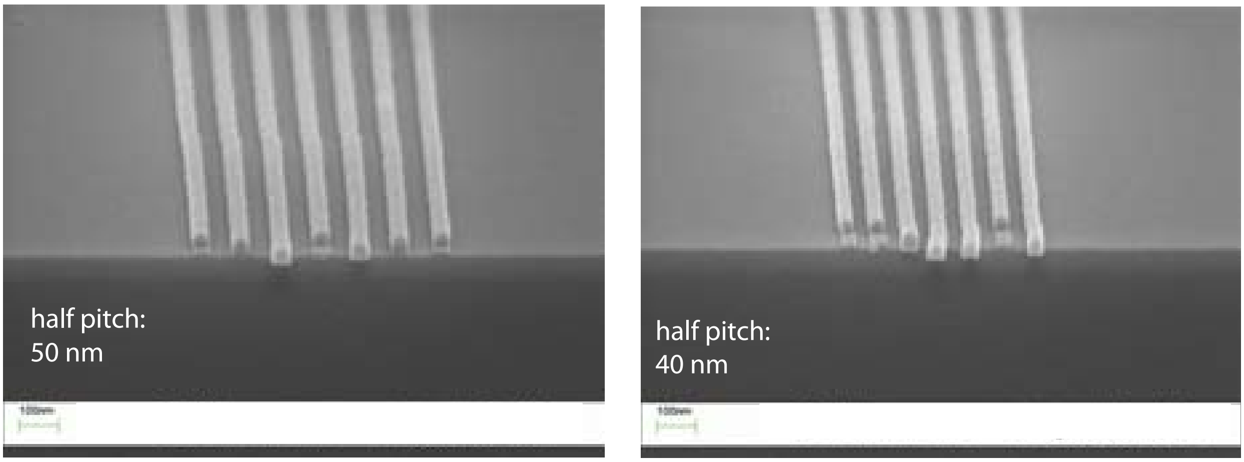


*Figure 6. Pattern after chrome hard mask etch: 50nm HP and (left) and 40nm HP (right).*

of 40nm L/S in a 1:1 pitch has been printed. To deal with the small exposure field, multiple exposures and a special arrangement stepping the image field about image field size + offset in x direction and image field size - offset in y direction has been used.

### 2.6 Process sequence

The sequence to fabricate OMOG masks consists of four steps which are resist patterning, hard mask etching, hard mask transfer etching, and hard mask removal. The process flow is shown schematically in Fig. 3.

## 3. Results and discussion

### 3.1 Electron beam reference HSQ process

It is a commonplace that resolution is determined by both writing tool parameters and resist performance. In the past impressive resolution capability has been demonstrated with the high resolution variable shaped electron beam writer Vistec SB352.[9] Running experiments with diluted HSQ FOX-12, groups of seven lines in a 1:1 pitch down to 35nm have been resolved well (Fig. 4). The resist shows a good adhesion on chrome while no notching or footing has been observed. According x-section results, resist thickness (post development) is around 50nm which is in the designated range to come to an in-situ resist removal during MoSi absorber etching step.

LER (3s) and LWR (3s) have been determined for both 40nm HP and 35nm HP features which are 3.4nm / 3.9nm and 4.8nm / 5.7nm respectively (Fig. 4). The values for the resist itself might even be better as there are butting effects observable caused by shot mounting during writing.

### 3.2 Proton multi-beam HSQ process

For proton multi-beam patterning, same resist coating conditions have been used. Due to the selected exposure technique, smallest features are dense lines 1:1 with 40nm HP. This pattern has been resolved well (Fig. 5). The proton exposed resist shows a good adhesion on chrome without any visible footing. Resist thickness (post development) was determined to be in the same range as for the electron beam experiments. Again LER (3s) and LWR (3s) have been determined to be 2.2nm and 3.3nm measured for 40nm HP features (Fig. 5). These values are slightly better than for the electron beam experiments, which may be caused by absence of butting and a higher energy contrast.

### 3.3 Chrome hard mask etching

Chrome hard mask was etched in an Oerlikon Gen IV chamber with a chlorine based process. This process mainly corresponds to supplier

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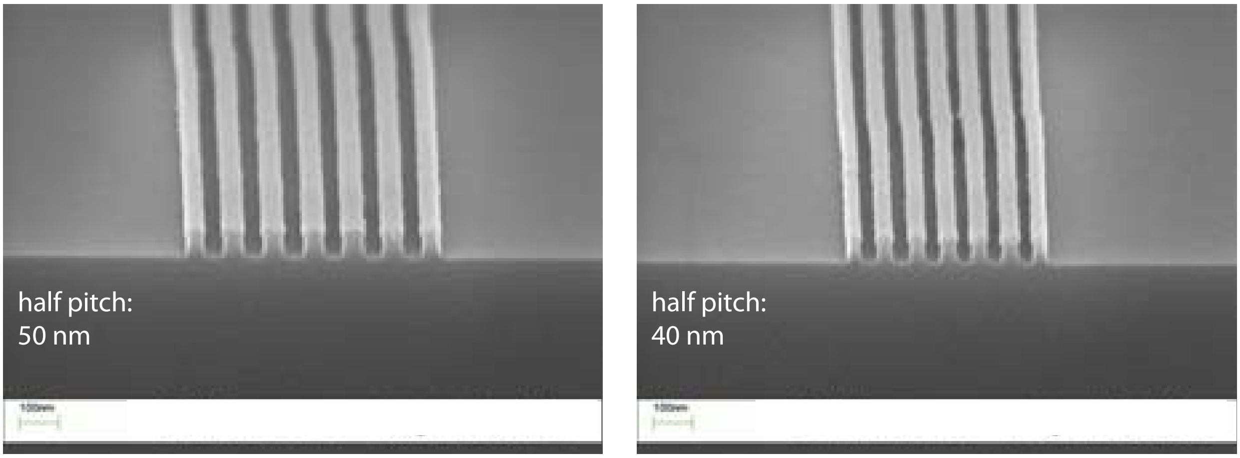


*Figure 7. Pattern after MoSi absorber etch: 50nm HP and (left) and 40nm HP (right).*

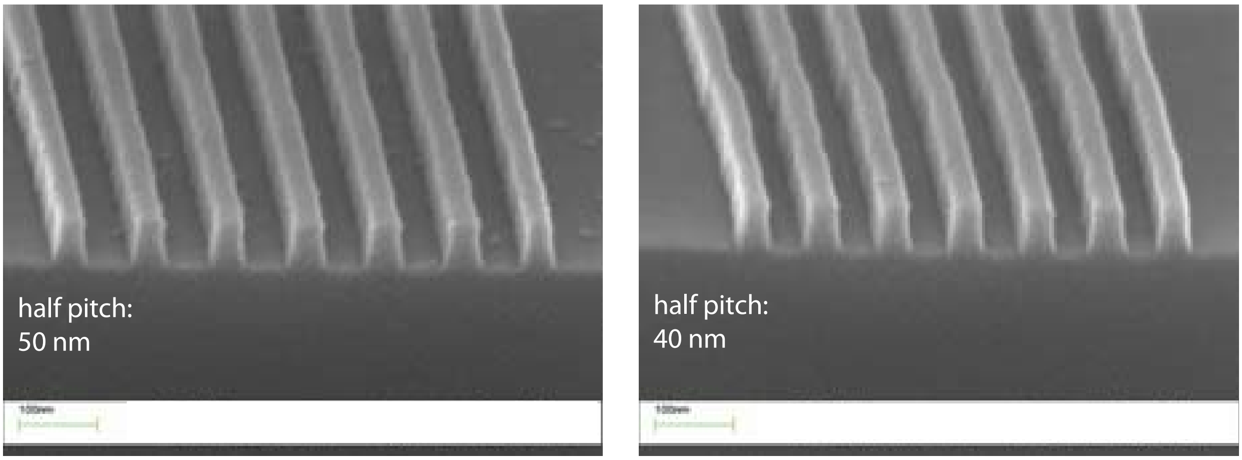


*Figure 8. Pattern after chrome hard mask strip: 50nm HP and (left) and 40nm HP (right).*

recommendations containing some minor modification to deal with thin layers and HSQ. One of the main topics has been avoiding of an undercut of the resist mask resulting in both bad absorber profiles and a thinning of the absorber. End point was monitored by optical emission spectroscopy (OES) applying an overetch of additional 22.5% of the main etch time. Cross section of a sample (Fig. 6) shows good profiles without any undercut compared to the HSQ mask.

### 3.4 MoSi absorber etching

Transferring the hard mask into the underlying MoSi layer was done in an Oerlikon Gen III chamber. Starting point was a fluorine-oxygen process usually used for standard MoSi applications with some minor modification to deal with the HSQ layer on top of the hard mask. Beside the need for straight profiles, goal was also to get rid of the remaining HSQ which of course must not influence the profile shape. End point was monitored again by OES. Running the first processes, a slight undercut as been observed (Fig. 7), resulting in a sidewall angle of about 85° (Fig. 13). To check for an even better slope, gas composition has been modified in a second loop. Cross section of a sample shows this process resulting in a reduced undercut and slightly steeper profiles of around 86° (Fig. 14).

### 3.5 Chrome hard mask strip

After the absorber has been etched, remaining hard mask has to be removed. This might be done by the use of a suitable wet etching chemistry or a dry etch step. For this work, a commercial available wet etch solution containing an acidic solution of a ceric salt was used. Due to the low thickness of the hard mask layer, process time was selected to be 10min at room temperature. Applying this treatment, eventually remaining residuals of HSQ on top of the hard mask would also be removed by lift off. Taking into account the feature profile after MoSi etch, no additional bias due to this process step could be observed (Fig. 8). While some samples show particles after the stripping process, manual mask processing as well as the subsequent SEM sample preparation are expected to be the reason for that.

### 3.6 Result electron beam reference process

Running the three previously described process steps, HSQ resist patterning, hard mask etching, and hard mask transfer etching in series, MoSi features have been realized (Fig. 8). Looking on shape and resolution, the profile angle is around 85° while the smallest feature resolved is 40nm HP. Reasons for not resolving the ultimate resolution of 35nm as shown in HSQ are probably small variations in

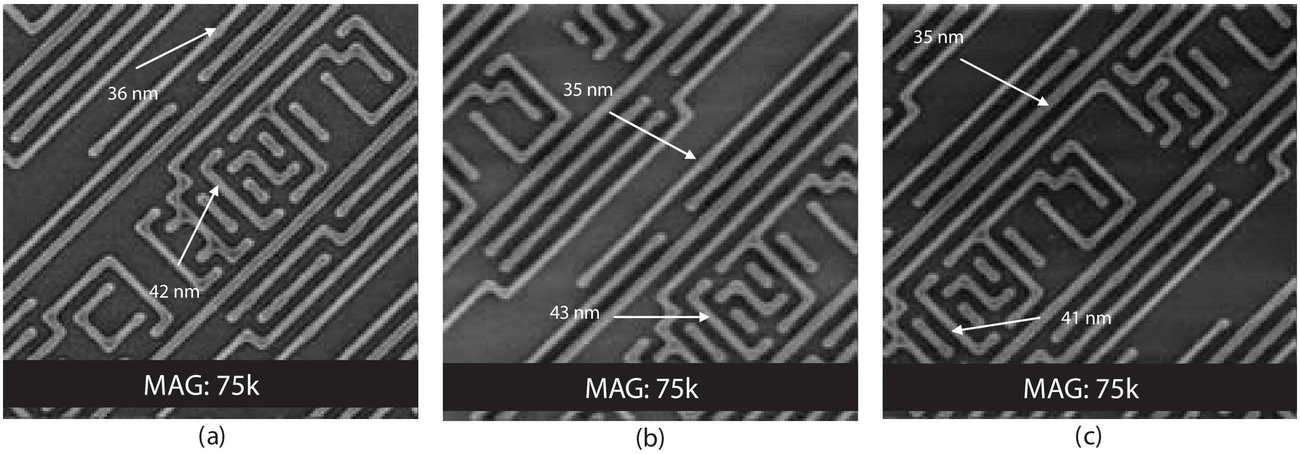


*Figure 9. Sample Device layer: Pattern after hard mask etch (a), absorber etch (b) and hard mask strip (c).*

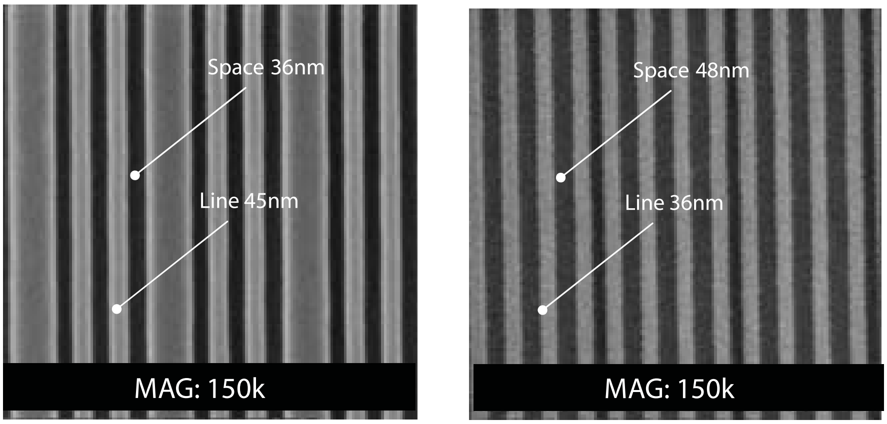


*Figure 10. Pattern after MoSi absorber etch: Layout A (left) and B (right).*

the resist patterning process. Bias of hard mask-to-absorber transfer is below 2nm measured at the real device pattern (Fig. 9). Visibility of small edges along the MoSi sidewall also indicates high pattern fidelity of the process. In terms of LER and LWR, measurement on the real device pattern results in 3.6nm (3s) and 4.7nm (3s) respectively for a 32nm line.

### 3.7 Result proton multi-beam process

Similar to the electron beam reference process, the subsequent running of HSQ resist patterning, hard mask etching, and hard mask transfer etching, good results in MoSi could be realized (Fig. 11 to Fig. 14). In terms of shape and resolution, profile angle of around 85° could be achieved while the smallest feature resolved is 40nm HP. The actual exposure regime has not allowed smaller features. The CHARPAN PMLP proof-of-concept tool resolution capability has been shown to be 16nm hp in 20nm HSQ resist when using 10 keV protons [10].

Running the three previously described process steps, CD measurements have been performed for the resist mask, after MoSi absorber etch, and after chrome hard mask strip. Starting with values for LER/LWR of 2.2nm (3s)/3.3nm (3s) for resist, chrome hard mask and absorber etch leads to an increase of about 1nm (3.4nm (3s) / 4.5nm (3s)). After hard mask strip, the values came back very close to the starting point (2.0nm (3s)/2.9nm (3s)). Therefore the main part of the values seems to be caused by patterning of the chrome hard mask. In total the performance of the MoSi pattern are mainly determined by the quality of the resist pattern. This leads to the conclusion that OMOG technique is a very smart and promising approach for future mask nodes.

### 3.8 Writing time estimation

Beside resolution and LER, writing time is a key topic for future nodes. Assuming a perfect tool base, throughput would only be determined by the writing time. Areal exposure speed may be calculated as the quotient of beam current and the product of exposure dose and pattern density. Solving this equation for a beam current of 45nA, a dose of 25µC/cm$^2$ and pattern density of 50% an areal exposure speed of 3.6•10-3 cm$^2$/s results. By dividing the mask area to be exposed through this value, the total writing time can be calculated. Assuming a chip size of 26mm x 32mm, the corresponding mask area would be 104mm x 128mm which is around 133cm$^2$. Therefore pure writing time is around 10 hours per mask. For a real throughput analysis of an ion exposure tool, several additional times have to be taken into account as mask exchange, registration, redundancy exposure and stage performance.[2]

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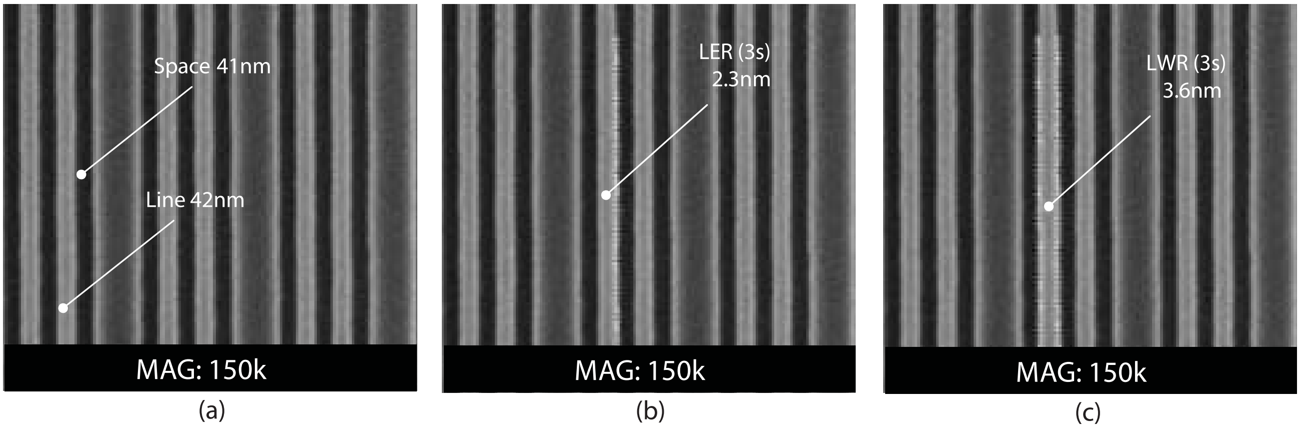


*Figure 11. Pattern after chrome hard mask strip (Layout A): CD (a), LER (b) and LWR (c).*

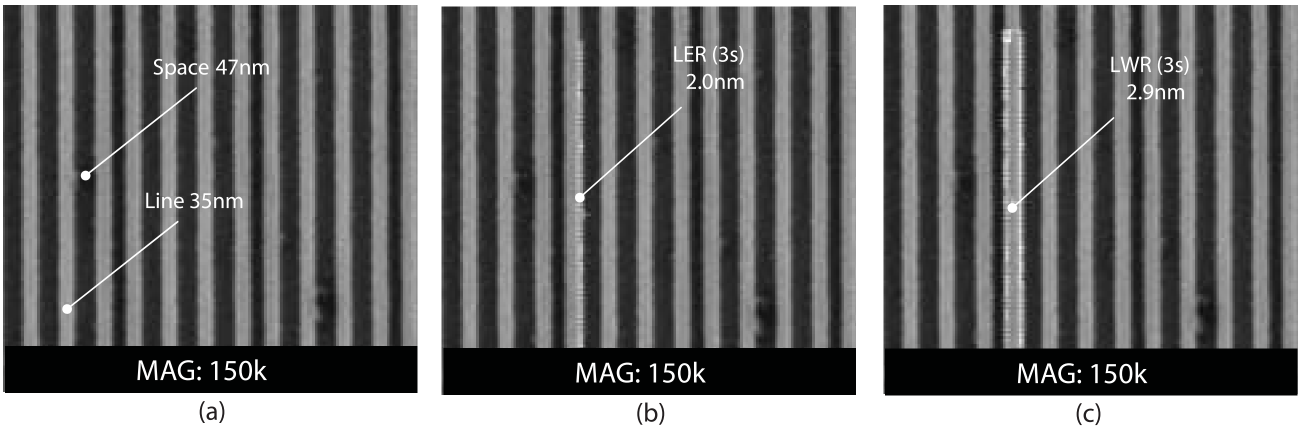


*Figure 12. Pattern after chrome hard mask strip (Layout B): CD (a), LER (b) and LWR (c).*

## 4. Conclusion

Combining OMOG blanks developed by Shin-Etsu's with the sensitive resist HSQ and a proton multi-beam pattern generator a MoSi feature resolution of 40nm HP has been shown which is neither limited by blank material nor by pattern transfer step. Actually a sidewall angle of approximately 85° could be obtained. In terms of LER (3s) and LWR (3s) which are 2.0nm and 2.8nm respectively, patterning results are superior to today's nCARs. Nevertheless specifications of the ITRS Roadmap for the 22nm mask node are not met yet. Going through the entire process chain, it could be shown that LER and LWR of the resist mainly determine the quality of final MoSi patterns. Therefore it can be concluded that OMOG technique is a very smart and promising approach for future mask nodes. Concerning throughput, expected writing time per mask for the 22nm node based on the current results has been estimated to be around 10 hours which may come in an area of interest for mask makers.

Further work will concentrate on process optimization for MoSi sidewall angle, LER, and ion multi-beam exposed device layers as well as possible alternative resist systems.

## 5. Acknowledgment

This work has been supported by the European Commission through funding of the FP6 Integrated Project CHARPAN (Charged Particle Nanotech / IP 515803-2 CHARPAN / www.charpan.com) and by the Ministry of Economic Affairs of Baden-Wuerttemberg.

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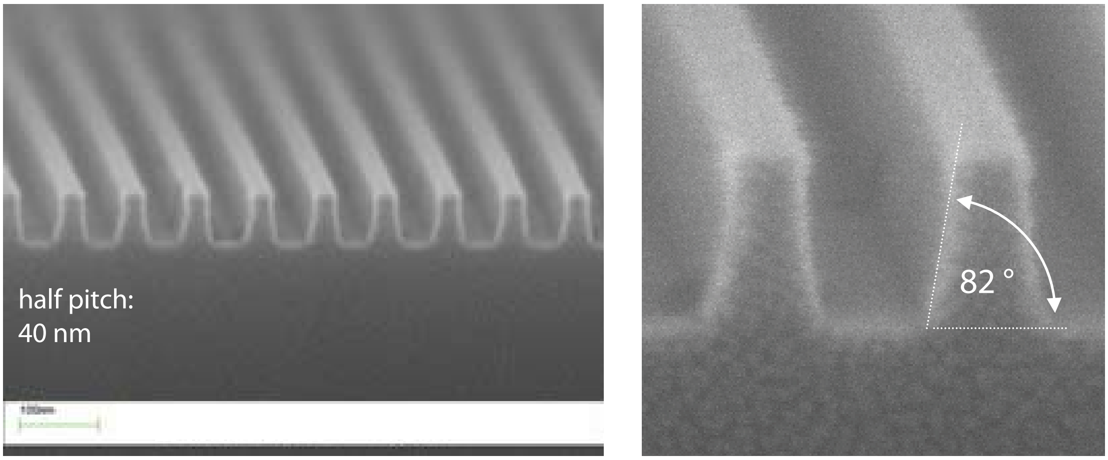


*Figure 13. X-section of final mask pattern: Overview (left) and profile angle (right).*

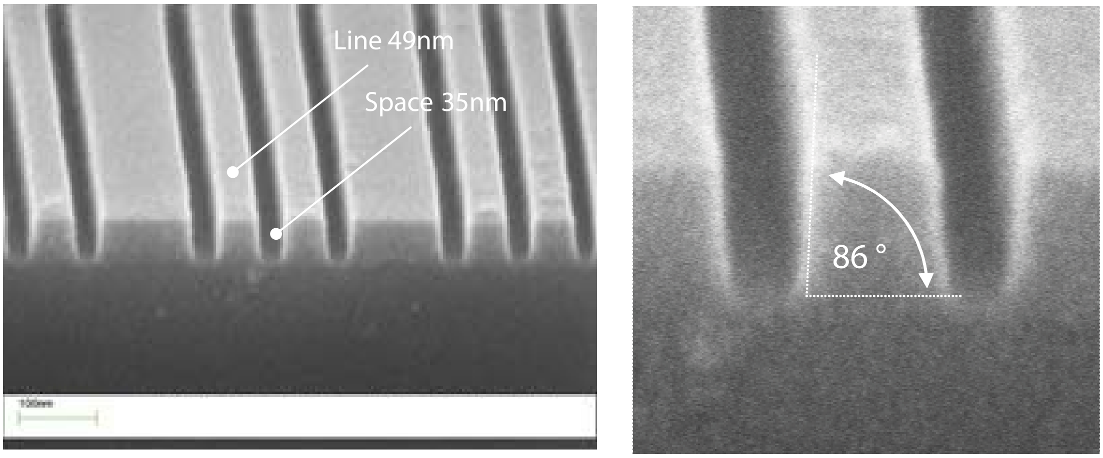


*Figure 14. X-section of final mask pattern (optimized etch process): Overview (left) and profile angle (right).*

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# Industry Briefs

## Aera2 for Lithography

*By* **David Lammers,** Semiconductor International

With double patterning coming into volume manufacturing, fabs must ensure that critical dimension uniformity (CDU) is maintained on masks after multiple exposures and haze buildup. Applied said that by using the Aera2 system's IntenCD aerial inspection technology in the fab's lithography cell, manufacturers can improve wafer CDU by >20%, increase device yields, and lower the per-wafer cost of patterning. CD uniformity specifications are very tight at the 45 nm node and below, especially for double patterning, and at least half of the variation in CD comes from the mask, said Tom St. Dennis, senior vice president of Applied's Silicon Systems Group.

The IntenCD technology creates CDU maps from the aerial image of the entire reticle. Applied says that by replacing wafer-based measurements with IntenCD maps, the time to decision about the mask's usability shrinks from two days to as little as an hour. Also, the improved uniformity data makes it possible for scanners to compensate for CD variations, improving linewidth accuracy. The in-fab inspections will allow fab managers to stretch mask lifetimes, the company said. Mask properties change dynamically and non-uniformly with cumulative exposures, inducing CD errors from haze defect growth and pellicle degradation, a press release stated. By replacing traditional fixed mask reconditioning intervals with predictive scheduling, fab managers can use the Aera2 system to minimize mask reconditioning cycles, increasing mask lifetime and availability. The inspection tool can be used with the company's Tetra reticle clean system, eliminating the need to send masks outside the fab for reconditioning.

## Photronics Quarterly and Annual Revenue Up Slightly

*By* **Semiconductor International**

Maskmaker Photronics Inc. (Brookfield, Conn.) said today that its financial results for the fourth quarter of fiscal 2008 were in line with the expectations stated in its Dec. 4 release, with quarterly sales of $103.3M, up 1.7% from $101.6M in fiscal 4Q07. Annual revenue was also up slightly over 2007, thanks to sales for flat panel displays.

Semiconductor photomasks accounted for $77.5M (75%) of revenues during the quarter, with sales of flat panel display (FPD) photomasks making up the other 25% at $25.8M. Sales for fiscal 2008 were $422.5M, up slightly from the $421.5M reported in fiscal 2007. Year-over-year, semiconductor photomask revenues decreased 7.2%, but FPD photomask revenues increased 31.1%.

The financial results for the fourth quarter reflect solid execution in the face of a difficult market environment, said Constantine S. Macricostas, Photronics, chairman and interim CEO, in a statement. Photronics was pleased that the strict cost control measures allowed to be profitable for the fourth quarter. For the full 2008 fiscal year, the FPD business performed well, offsetting softness in the integrated circuit mask market. Now that Company's credit facility is in place, the goal is to return to profitability on an annual basis and to strengthen the balance sheet. Photronics remains committed to executing our cost reduction and growth strategy.

# Join the premier professional organization for mask makers and mask users!

## About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

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- Eligibility to hold office on BACUS Steering Committee

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### Corporate Membership Benefits include:

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- One online SPIE Journal Subscription
- Exhibit Space discount of 8% at either the Photomask or Advanced Lithography Symposium
- Listed as a Corporate Member in the BACUS Monthly Newsletter

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## Calendar

### 2009

**SPIE Advanced Lithography**
22-27 February
San Jose, California, USA
**spie.org/al**

**Photomask Japan**
8-10 April
Hotel Pacifico Yokohama
Yokohama, Japan
**www.photomask-japan.org**

**SPIE Photomask**
14-18 September
Monterey Marriott and
Monterey Conference Center
Monterey, California, USA
**spie.org/pm**

You are invited to submit events of interest for this calendar. Please send to lindad@spie.org; alternatively, email or fax to SPIE.

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*International Headquarters*
P.O. Box 10, Bellingham, WA 98227-0010 USA
Tel: +1 888 504 8171 or +1 360 676 3290
Fax: +1 360 647 1445
customerservice@spie.org • SPIE.org

*Shipping Address*
1000 20th St., Bellingham, WA 98225-6705 USA

**SPIE *Europe***

2 Alexandra Gate, Ffordd Pengam, Cardiff,
CF24 2SA, UK
Tel: +44 29 20 89 4747
Fax: +44 29 20 89 4750
spieeurope@spieeurope.org • www.spieeurope.org